Enabling Collaborative Engineering and Science at JPL[1]

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Abstract

We examine the issue of distributed collaboration at the Jet Propulsion Laboratory (JPL). With the goals of "faster, better, cheaper" missions, an efficient, seamless collaboration capability is critical to future JPL space exploration missions. We assert that the current capabilities for distributed collaboration internal to JPL, as well as external, are unsatisfactory. This paper provides a vision of greatly enhanced distributed collaboration capabilities in the near future and into the far future. Our vision focuses primarily on distributed collaborative engineering and science.

We believe enhanced capabilities are necessary in two collaborative paradigms: the virtual conference and the shared virtual workspace. We describe these collaborative paradigms, and discuss the tools that exist and the additional capability necessary to achieve the collaborative vision with respect to the types of data we typically work with at JPL. We identify the following types of data frequently exchanged in collaborative activities: project planning data, design data, notes/documentation, communication data, analysis/performance data, verification data and scientific data. Our analysis shows that at present there is good GroupWare support for project planning data and

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notes/documentation data. Support is improving for design data. Other data types have no or sporadic support at best.

Keywords: collaboration, CSCW, GroupWare, collaborative engineering, interoperability, virtual shared workspace, virtual conference.

1. Introduction

The size and complexity of JPL missions and projects implies that many people from different disciplines are involved. The engineering and science expertise necessary for mission success is distributed in various JPL organizations. Thus, often people who collaborate on a task occupy disparate locations within JPL. Furthermore, missions and projects frequently utilize expertise from industry. Many involve contractors or other NASA centers. The new requirements at JPL for more missions at lower cost intimate the need for distributed collaborative solutions that allow engineers and scientists to do and share their work quickly and conveniently and thereby inexpensively.

To date, interaction among collaborators involves meetings that are costly and usually involve the inconvenience of travel. Other interactions, such as telephone conversations and email messages, do not provide team members complete knowledge of the current state of the project or access to the latest project data. The best-of-practice solutions for sharing project data require team members to use a single tool or family of tools (such as Microsoft Office). These solutions are insufficient for engineers and scientists who typically use many different tools and diverse computing platforms. An engineer who uses Matlab for simulation, for example, is unwilling to learn another simulation tool in order to be compatible with other team members. We envision collaborative environments that support distributed design and science exploration both near and long-term. These environments will enable efficient, robust and seamless exchange of information while enhancing, rather than restricting, the way team members operate. Rather than developing new specialized tools, this paper advocates building these collaborative environments through integration and interoperability.

The need for collaboration in industry is widely recognized. A large class of tools, entitled "GroupWare", supports collaboration. This paper presents many such tools from the familiar e-mail programs (e.g., Eudora) and document management tools (e.g., Xerox's DocuShare), to the less familiar virtual conferencing systems (e.g., NetMeeting) and engineering design tools (e.g. Parametric Technology Corporation engineering suite), and finally to the obscure data-conferencing tools (e.g., MeetingWorks) and extensible collaborative engineering environments (e.g. Lockheed-Martin's Simulation-Based Design). We observe that the available technology focuses primarily on administrative related tasks, such as scheduling meetings and managing documents. There is little support for the varied work we do at JPL in terms of engineering (designing, developing, manufacturing and operating devices) and of science (collecting and analyzing data). This paper presents the requirements for comprehensive collaboration support necessary for JPL.

This paper is organized as follows. The remainder of this section contains some definitions that are used throughout the papers about collaborative paradigms. In section 2 we sketch our vision for collaboration, in particular we describe an example collaborative engineering effort. In section 3 we categorize the work we do at JPL in terms of the type of data that is used in collaboration. Section 4 illustrates the features we require for collaborative environments for each of the data types from section 3. In addition, we discuss available tools for collaboration in section 4. Here we find that collaborative support exists primarily for project management and documentation. Section 5 attempts to explain why the support is concentrated in these areas and brings forth the key issues or barriers to creating collaborative computing environments. Finally, we conclude in section 6.

Collaborative Paradigms

The field of Computer Supported Cooperative Work (CSCW) divides collaborative work along two axes: time and place [1]. Collaboration can occur at the same time (synchronous), as in a meeting, or at different times (asynchronous). In the place domain we have same-place interaction (face-to-face) and different-place interaction (distributed). These axes define the four paradigms of table 1. Every tool that supports cooperative work falls into one of these four paradigms. This paper focuses on the problem of distributed collaboration. Thus, we will devote our interest to the virtual conference paradigm and the shared virtual workspace paradigm.

PLACE	**TIME**	
	Synchronous	**Asynchronous**
Face-to-face	Typical Meeting	Typical Workspace
Distributed	Virtual Conference	Shared Workspace

Table 1. Collaborative Paradigms

2. The Distributed Collaboration Vision

This section depicts a distributed collaboration vision. We illustrate this vision within the context of a distributed collaborative engineering scenario. (Note that although we roll out this vision in the context of engineering design, the same elements can and should be applied to all other aspects of engineering and science. We envision collaborative environments not only in the design phase of a project, but throughout the project cycle of design, manufacturing, assembly, integration, test and operation.

One way to rapidly design a new product is to start with an existing design from a similar product. At present, reuse of design expertise and design knowledge is achieved primarily by reusing engineers. That is, if we need to design an autonomous robotic rover for Europa, we employ the same person who designed the autonomous robotic rover for our previous Mars mission. Our vision for collaborative engineering makes heavy use of an institutional knowledge base. This knowledge base would be available on the Intranet and would contain all prior engineering experience at JPL per subject area. Every project would publish and archive their designs to the knowledge base along with associated design documentation, the design process used and various trades (i.e., why this design was chosen over other possible designs), documentation for development of the project, as well as manufacturing and testing information for the object. This knowledge base should minimize the dependence of projects on a small group of extremely experienced and knowledgeable engineers.

In our vision, the first step for embarking on a new design is, therefore, to consult the engineering knowledge base. Let us suppose that the engineer finds several relevant designs. He may use documentation in the knowledge base to select the best baseline design for the current application. Furthermore, due to the associated documentation, the project engineer immediately knows the strong and weak points of their initial design.

Once a baseline design is selected the engineer will bring it out of a product design archive and into the collaborative engineering environment. We perceive the need for two environments to support the two paradigms for distributed collaboration. The first environment supports the shared virtual workspace paradigm. In this environment the design data and documentation is available to all team members anytime and anywhere. The environment supports heterogeneous tools so that each team member can view, modify and analyze the design using their preferred tool. Some of the challenges in creating this environment are data management, tool interoperability, team awareness, contention resolution, and workflow enforcement. The virtual meeting environment will use the latest video-conferencing capability to bring the distributed participants together. The real innovation of this environment, however, is in data-conferencing. The virtual meeting environment incorporates the shared virtual workspace environment. Thus, team members can simultaneously view, modify and analyze the mission or product design during any part of the lifecycle during the meeting.

When we extend this vision to the far future the two environments blend into one environment which is heavily dependent on virtual reality capability. In this environment, the design tool will be a virtual-reality 3-D tool such that the designer can "see and feel" the object as they are designing it for a given mission application. Furthermore, the shared virtual workspace and virtual meeting environments merge into a virtual reality meeting environment that allows any number of people, located anywhere, to use the tools at any time. This vision is reminiscent of a combination of Star Trek's holo-deck, which allows people to interact with holographic images of other people as well as objects, joined with Star Trek's intergalactic meetings, where holographic images of participants interact with the participants on the starship. Naturally, the far-sighted vision seems inconceivable at present, but we look to CSCW and virtual-reality research to improve these capabilities [2].

In the rest of the paper we restrict our comments to the near-future vision and the capabilities we have or need to develop to create the shared virtual workspace environment and the virtual meeting environment.

3. Data Types for Collaboration at JPL

The engineering and science work at JPL uses and produces diverse data.

Project Planning Data refers to the data involved in managing large projects, for example, managing deliverables, creating timelines and project mile-stones, assessing the success of the project through a review process, managing meetings and enforcing the project workflow. Project planning data is very dynamic. It requires both distribution and access control.

Notes/Documentation is probably the largest body of data created by JPL. Notes are usually written by hand in a personal notebook. Documentation is typically an afterthought in a project. Thus, the majority of knowledge amassed by the team remains with them. We want projects to capture their knowledge and make this information easy to find and accessible to all parties.

Communication Data is the data used by team members to interact with each other. Traditional communication among distributed teams involved face-to-face meetings, telephone conversations and electronic mail. New communication paradigms involved tele- or video-conferencing. These communication paradigms are sometimes web-based and may be on dedicated networks.

Design Data is the data created in the process of engineering design. Design data is comprised of a large number of interacting parameters and relationships. This data must be accessible to heterogeneous design and analysis tools. Versioning and workflow are also essential to collaboration on design data.

Analysis/Performance Data is data obtained about the design from simulation and analysis tools. This data type includes analysis of relevant performance measures such as volume, mass, velocity, temperature, power, structural loads and cost. This data type must be integrated with the design data to enable effective collaboration.

Verification Data is data generated in the process of manufacturing and testing of a system or instrument. Examples of verification data are the level or current output by a module, heat resistance of a material and more. We want team members to have access to the verification data itself, rather than a summary of the testing procedure. Further, we want real-time access to verification data in a virtual conference setting.

Scientific Data is the purpose of JPL missions. The scientific data produced by JPL missions is studied by large numbers of scientists worldwide. Thus, distributed, timely access to this data is critical. Furthermore, missions generate quantities of data that are beyond our capability to analyze. Therefore, it is insufficient to capture the knowledge we can extract from this data today because tomorrow we may be able to learn more from the same data. We must store this data for the long run and make it accessible to future generations of scientists.

The rest of this paper will discuss in depth the requirements of distributed collaboration with respect to each of the above types of data. We discuss tools that solve the problems associated with each data type. For most data types tools that offer a partial solution will be presented. We seek to describe a comprehensive framework for distributed collaborative science and engineering. This framework supports all the above types of data in both the shared virtual workspace and virtual conference paradigms. We identify areas where existing tools are inadequate to support this framework.

4. Distributed Collaboration Environments

This section provides an in depth analysis of the environments needed to attain the collaborative vision of section 2. We examine tools that enable collaboration. In this case, we do not refer to the tools that engineers and scientists use to do their work. Rather, we assume that engineers and scientists have preferred tools. We attempt to address the problem of distributed collaboration without forcing team members to change their working environment. Instead we want to construct a framework that allows them to interoperate their preferred tools using integration infrastructure, thereby creating a seamless collaborative environment. For each data type we describe the capabilities we deem necessary for a productive shared virtual workspace and virtual meeting. In addition, we examine existing GroupWare offerings and indicate the support provided by each product as compared with the desired capabilities.

Project Planning Data

The shared virtual workspace must provide access to project information, such timelines and review information. In addition, a messaging capability is necessary. Preferably one that puts the information in the user's hands rather than forcing the user to search for it. The portal strategy seems ideal for implementing such a workspace. In addition to information storage and retrieval we normally expect on the Internet, Portals provides information push and customization technologies. One offering in this category is Datachannel's Rio [3] which is an enterprise information portal. Rio's capabilities include end-user publishing and personalized navigation and delivery, including automated updates. Several other portal products are available, with similar capabilities, e.g., Netscape's Custom Netcenter [4] and Plumtree [5]. Compared with document management systems that focus on document maintenance, portals emphasize information exchange. Portal systems typically provide some core capability and extensibility through a programming API, thereby meeting our requirements for flexibility.

There are also several good offerings for project management data in the virtual meeting paradigm in the guise of decision support software for meetings. For example, GroupSystems [6] provides tools for managing group processes such as brainstorming, information gathering, voting, organizing, prioritizing, and consensus building. Among the key advantages of these tools are the ability for all the participants to contribute their ideas simultaneously and anonymity of statements and votes. The GroupSystems tools can be used in a same-time or distributed meeting setting. For distributed meeting, tele- or video-conferencing tools can be used for the communication data while the GroupSystems tools are used for the planning data. GroupSystems is currently available and has facilitated several successful collaborations, for example at Nokia Telecommunications, Cheveron Pipe Line, and Distributed Strategic Planning.

Two additional offerings - Enterprise Solutions' MeetingWorks Connect [7] and Facilitate.com [8] - provide another solution for same-time different place meeting support. The tools provide similar capabilities for entering ideas, votes and comments. Because participants are located outside the meeting room, these tools use the Internet or corporate Intranet. An additional advantage of the web-based technology is platform independence. Unlike most of the GroupWare offerings, MeetingWorks Connect and Facilitate.com can be used by any browser-enabled platform.

Documentation Data

The virtual shared workspace for documentation data should support large number of documents in a variety of formats. It should be the realm of the document management environment to provide the latest version (where the latest version means the actual document, not a copy or a picture such as a pdf file). Users should be able to view and update documents based on their access privileges. The environment must support flexible document organizations, for example complex linking among documents, and excellent searching capability.

Several document management systems provide many of the requirements above.

Xerox's DocuShare [9] lets team members use your corporate Intranet or extranet to set up a virtual information-sharing environment. Users can easily post, retrieve and search for information that resides in familiar nested folders. In addition, users can adapt and customize DocuShare to suit the specific needs of any workgroup or project. The DocuShare environment provides instant and controlled access to information. OpenText's Livelink [10] is another document management system for the enterprise. In addition to the above capabilities, Livelink provides a workflow manager, discussion groups and news channels, which make use of new information push technology. These systems can be accessed by anyone with a Web browser, whether they're working on a PC, Macintosh or Unix computer. Corporate portals, such as DataChannel's Rio and Netscape Custom Netcenter are another option for shared documentation data workspaces.

Thus, existing products anywhere access to documents with access right protection, real-time updates, update notification and more. The drawbacks of existing environments are a rigid organizational structure, which limits the user's browsing ability, and so-so searching capability. Utilization of new standards, in particular the Extensible Markup Language (XML) [11] and its derivative standards to improve these technological limitation. For example, XML Linking Language (Xlink) will enable improved browsing ability using bi-directional and multiple links [12], and the Resource Description Framework (RDF) enables better searching capability using enhanced meta-data description [13].

The virtual conference should enable participants to view and update documents during the course of the meeting. Electronic whiteboard technology is the best current contender for providing this capability. SMART Meeting Pro [14] is meeting information management software, similar to GroupSystems and MeetingWorks. In addition, SMART Meeting works with the SMART Board, an interactive whiteboard It combines the look and feel of a regular whiteboard with the computer so you can save and print notes, collaborate on electronic documents, share information and run multimedia materials. The SMART Board, however, provides same-place viewing and update, not distributed updated. A distributed, synchronous whiteboard is provided by Blackboard.com [15] - a web service that enables instructors to add an online component to their classes, or even host an entire course on the Web. Further capability is needed to integrate whiteboard (or similar) technology in a video-conferencing setting.

Communication Data

The virtual shared workspace must provide an asynchronous communication mechanism for messaging and update notification. Email provides an excellent messaging capability, with wide availability and anytime/anywhere access. However, it is easy to miss a message sent by email because the user either did not open his mailbox, or had too many messages. Thus email is inappropriate for urgent (must see) messages. Many environments provide their own messaging systems, but checking messages in a number of software tools becomes cumbersome. Messaging systems should be highly configurable so that the user can choose where to receive various types of messages. For example, one could configure update notifications for project X as well as email notification from project X personnel to display in the browser, which is opened at startup.

Synchronous communication for a virtual conference must provide real-time, high fidelity communication. Several modes of synchronous communication are currently available: telephone conference, chat capability, and video conferencing. JPL, like many other companies, has adopted all of these solutions. The primary limitation of these technologies is that they fail to provide the typical meeting experience. Thus, people are often reluctant to use these technologies as a substitute for face-to-face meetings.

Another capability we want in virtual conferencing is tight integration with the data. In typical meetings participants can walk up to the same whiteboard and collaborate on notes and drawings. Similarly, they can take turns using a computer to modify a document or use an application. We would like the distributed virtual conference to provide similar features. This set of features is known as data-conferencing, which is the latest trend in GroupWare. Many data-conferencing offerings are springing up [16]. For example, Microsoft's NetMeeting [17] provides Internet based audio/video conferencing integrated with Windows applications. We advocate enhancing data-conferencing infrastructure to facilitate integration of a wide variety of tools for all the data types we are concerned with at JPL.

Design Data

The virtual shared workspace for design data must consist of an environment that allows the use of any tool on the design data, including tools that perform different functions, e.g., design, simulation, costing analysis. Successful design collaborations today restrict the collaborators to a small set of tools. Integrated collaboration efforts typically to incorporate a small set of domain specific tools. While these collaborative efforts achieve their specific goal they do not forward the overall capabilities of the organization. The tools do not address similar collaboration needs in another domain. Examples of collaborative environments of this nature are Parametric Technology Corporation Pro/ENGINEER suite of tools [18], and JPL's Product Design Center [19].

In contrast, Lockheed Martin-ATC has developed a Simulation Based Design (SBD) tool [20]. SBD is a distributed collaborative environment for engineering design. It provides support for a simulation based design paradigm that includes virtual prototyping rather than physical prototyping. The simulated processes show significant payoff in time and cost of design, in particular for new technology insertion. The SBD environment supports SBD processes by integrating applications, providing the underlying communication backbone and a unified Graphical User Interface. The SBD environment contains an object-oriented model of the product. All the tools in the SBD environment use this model as a common "logical" database. The environment includes a variety of tools including 3D visualization, requirement tools, engineering tools, commercial tools, workflow tools, and cost tools. In addition, the extensible design of SBD enables users to add functionality using their own preferred tools and applications (including legacy applications) to the SBD environment. Thus, the SBD provides the collaboration services such as data management, update notification, etc. while maintaining flexibility for the user.

The Pennsylvania State University's Applied Research Laboratory (ARL) SBD environment [21] is a similar simulation based design effort. The ARL SBD development emphasizes a specific naval application rather than the generic collaborative environment. The methodology, however, builds on broad and flexible infrastructure based on technologies and standards. In particular, the ISO STEP standard [22] enables exchange of graphical and engineering data from all engineering fields.

A virtual conferencing environment for design data should integrate a complete collaborative design environment, such as Lockheed Martins SBD environment, with a state-of-the-art video conferencing environment. For example, participants should be able to view, manipulate and modify a CAD model of the design simultaneously. The Lockheed Martin Multimedia Engineering Collaboration Environment (MECE) [23] provide an environment for real-time and spaced collaboration in a working project situation. MECE is a central feature of SBD, where it provides the designer's notebook and primary working environment. Designers use MECE to launch applications, document and record design decisions, and communicate with others via video conferencing, multimedia e-mail, and shared whiteboards and notebooks. It is not clear, however, whether MECE provides a true data-conferencing environment where data from distributed participants is coalesced in real-time.

Analysis & Scientific Data

Since the environment that enable collaboration on analysis data and scientific data have similar requirements we discuss these data types in a single section. The virtual shared workspace for science and analysis must provide shared access to data worldwide. This data creates a new challenge for data management since the data sets are typically very large. Furthermore, we need excellent archiving capabilities for centuries of data. Like the engineering workspace, this workspace must provide integration of user-preferred tools. In addition, for the analyst and scientist integration of user programs is critical. Lastly, a built-in feature for recording "experiments" should be built into this workspace. These records should be archived along with the data to enable future analysis.

Only one environment provides a scientific-like collaborative environment - TeamWave Workplace [24]. TeamWave Workplace uses a familiar "Rooms" metaphor. The environment is made up of several rooms that can be used for different purposes: working area, library or archiving, and conferencing. The workplace environment is equipped with a number of tools, including tools for audio/video communication, discussion groups, asynchronous messaging and organizational tools. The environment can be extended with additional, custom tools.

A new standard, the High-Level Architecture (HLA) [25] may be useful for enabling collaboration on analysis data. HLA is a standard architecture for distributed simulations developed by the DOD. DOD faces a new era of shrinking resources, more demanding operational requirements and much more technical capability. Large-scale modeling and simulation efforts in a distributed environment with inter-operable components can provide cost effective and affordable solutions to operational needs. The High Level Architecture provides a composable approach to constructing simulation federations.

The virtual conference for analysis and scientific data also bears many similarities with the virtual conference for design data. Once again, the data and tools should be available for viewing and modifying during the conference. For example, participants may initiate and view simulations. These "experiments" should be recorded and archived in the workspace.

Two tools provide distributed, synchronous collaboration for analysis and scientific data. Adept 26] provides an environment for collaboration and teamwork. MathConnex also provides tool interoperability through OLE Automation. Supported tools include Mathcad, MATLAB, and Axum for graphing, Excel or Lotus 1-2-3 spreadsheets and drawing and design tools. Collage [27] is a collaborative data analysis tool from NCSA. It is intended for doing data analysis either alone or simultaneously with several people who are on the same network. Collage features the following capabilities: viewing of data as images or in a spreadsheet, data analysis operations, paint operations (also provides whiteboard capability), palette manipulation, animation and text editing. In collaborative sessions all operations are shared, that is, data sets, functions and drawings, etc are distributed to all participants in the collaborative session. Neither of these tools provides the desired integration with communication data, i.e. video-conferencing, or infrastructure for tool integration.

Verification Data

Verification data produced while manufacturing and testing devices should be available in a shared virtual workspace as well as a virtual conference setting. At present very little verification data is available in electronic format at all, and none is available in real-time. The technology, however, for providing real-time data exists. It is the same technology that provides real-time radio signal over the Internet. Furthermore, many of the manufacturing and testing devices have the digital information. Once again, the missing piece is integration.

Data Type	**Collaborative Paradigm**	
	Shared Virtual Workspace	**Virtual Conference**
Project Planning	Rio	GroupSystems, MeetingWorks, Facilitate.com
Documentation	Rio, Livelink, Docushare	Blackboard.com, SmartMeeting
Communication	Email, Telephone	Telecon, Video-con, NetMeeting, Timbuktu Pro
Design	PTC Product Viewer, LM-ATC Simulation Based Design (SBD), STEP	C-TAD, MECE
Analysis	TeamWave, HLA	MathConnex, Collage
Verification		
Scientific	TeamWave	MathConnex, Collage

Table 2. Current Tools and Their Collaborative Applications

5. GroupWare Issues

The financial advantages of collaboration and, in particular, of enabling GroupWare have been demonstrated repeatedly [28]. Yet the engineering and scientific communities have not embraced these new methodologies and technologies. This section reviews the hurdles to accepting GroupWare at JPL and similar institutions or companies whose focus is large-scale engineering and science.

- Platform interoperability

The greatest limitation of GroupWare today is dependence on a specific platform. Many of the tools available today for collaboration support only the Windows platform. In an organization like JPL, engineers and scientists naturally use different computing platforms that are best suited for their needs. While most engineering tasks utilize the Windows platform, scientists prefer the computational power of the Unix platform. In addition, an extensive collection of legacy systems exists on Unix machines. Lastly, the organization's administrative staff prefers the Macintosh platform for ease-of-use. This heterogeneous computing environment immediately eliminates the bulk of GroupWare offerings. One category of solutions that alleviate this problem is the web-based GroupWare solutions.

- Application interoperability

Engineers and scientists have typically invested many years to gain expertise in the set of tools they use to do their work. For example, a designer is typically an expert user of one or a few CAD tools, and a scientist is an expert user of Matlab. The expertise and investment that they made in this set of tools includes shortcuts and a library of helper utilities. By comparison, few people invest much time in acquiring expertise at their e-mail program or their scheduling software. It is therefore much easier for an organization to mandate use of new scheduling software than a new CAD program. Indeed JPL's information services recently consolidated email and scheduling software, whereas consolidation of CAD tools is inconceivable. Mandating use of such expert tools is simply wasteful for the individual as well as the organization. The strategy this paper presents, therefore, requires the collaborative environment to be extensible, allowing integration of user-preferred tools into the environment.

- Sharing Knowledge

Experts are often reluctant to share their knowledge either because of the rewards of being "the expert" or because of barriers between different segments of the organization. The organization that wants to benefit from a sharing culture must promote a sharing culture. The organization must remove the barriers to sharing by rewarding experts for sharing knowledge as well as for holding knowledge.

- Protection and Security

Security is often a perceived barrier to computer-assisted collaboration. Individuals or project management may want to collaborate, but feel that the information is too sensitive to be transmitted electronically. We believe that this issue is strictly an issue of perception. Technology to support security, such as password protection and PGP encryption, exists and is easy to incorporate into a computing environment. Naturally we view an environment that does not provide these security mechanisms as inadequate. For the purpose of this paper, however, we assume that the security problem is resolved and focus on sharing rather than denying access to knowledge.

- More work now

Another barrier to computer-assisted collaboration is the up-front effort of setting up the collaboration environment. In any area of collaboration there is a tradeoff between the early costs and later benefits. The typical attitude of the individual is "why should I work more than I have to". Since it is the organization as a whole that will reap the benefits of the added effort, it is the organization that should supply the rewards for doing this work.

- Un-pressured environment

According to David Chapman at Collaborative Strategies [29] the companies that first adopt GroupWare are commercial, high-tech companies with small earning margin and heavy competition. The pressures of the high technology, commercial world have forced these organizations to undertake the organizational changes necessary to create a collaborative culture. At the aerospace and defense technology companies we are only beginning to feel the effects of a tighter budget. NASA's "Faster, Better, Cheaper" policy is now placing tough financial and schedule constraints on JPL mission. This era has already forced recognition of the value of collaboration. It will undoubtedly bring about the recognition of behavioral changes that must take place to enable collaboration.

To attain our goal of seamless collaboration across all JPL activities a combined technological and behavioral revolution must take place. Collaborative tools and environments need to be developed, and the operational processes must be revised to support a collaborative and sharing culture. Of the two conditions the second is the more difficult to achieve, and contrary to common belief, the one where most resources should be spent. A complete discussion of the organizational behavior aspects of collaboration is outside the scope of this paper. For a useful discussion of these issues see [28].

6. Conclusions

We have addressed the problem of collaboration at JPL. We outlined a vision of computer-supported collaboration in the two paradigms of shared, virtual workspaces and virtual conferences. We showed a need for collaboration across all activities at JPL with many types of data in mind: project data, documentation data, communication data, design data, analysis data, verification data and scientific data. Our vision consists of real-time sharing of information, use of user-preferred tools and operating platforms, re-use of existing knowledge, and integration of data and tools in virtual conferences.

Our analysis shows that at present there is pretty good GroupWare support for project planning data and notes/documentation data. Support is improving for design data primarily in the shared virtual workspace paradigm. Other data types have, at best, sporadic support and require significant development.

Section 5 discusses the barriers to adopting a collaborative environment and GroupWare. We must overcome significant technological difficulties such as heterogeneity of applications and operating systems. However, the technology to solve these problems is reasonably well understood. Thus, technological difficulties are secondary compared with the overwhelming barriers to creating a collaborative culture within the institution. A significant investment, of both time and money, is necessary to affect the desired changes in organizational processes and individual behavior. We believe JPL, and other engineering and scientific institutions, can achieve collaboration by working on the problem from both sides. Promoting collaboration at the organizational level, and building collaborative environments that adhere to the requirements presented in this paper.

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